

DIFFUSION FLAME ATTACHMENT AND FLAME FRONT PROPAGATION ALONG MIXING LAYERS

A. Liñán

E.T.S.Ingenieros Aeronáuticos
Universidad Politécnica de Madrid
Pza. Cardenal Cisneros 3
28040-Madrid (SPAIN)

1. INTRODUCTION

In diffusion flames mixing of the reactants takes place simultaneously with the chemical reaction. If the Reynolds number is large mixing takes place only in thin layers, which in most cases of interest are also vorticity layers, and thereby subject to the Helmholtz-Kelvin instabilities that lead to turbulence. When a diffusion flame is established in the mixing layer surrounding a fuel jet, the heat release due to the chemical reaction leads to changes in the flow structure and to a lowering of the effective Reynolds number around the flame sheet, so that it is often possible to observe very beautiful coherent structures. See, for example, Dumont and Borghi (1986).

The diffusion flame, under stationary conditions, is anchored close to the splitter plate, or injector lip, only for low values of the fuel jet velocity. If the splitter plate is cold the reaction is quenched close to the plate, and there is a small region ahead of the flame where the fuel and oxygen mix and are heated by upstream heat conduction from the flame. The size of the region of flame attachment is such that the Reynolds number, $U_N \delta_N / \nu_\infty$, based on the characteristic size δ_N , typical local flow velocity U_N , and initial kinematic viscosity ν_∞ of the air, is of order one. This is so as to allow for a balance of convection and heat conduction. For the typically large values of the Reynolds numbers, based on the fuel jet radius a , and maximum velocity U_1 , which are encountered in practice the flame attachment region is very small compared with a , and it is embedded in the wake region of the splitter plate.

Due to the large sensitivity of the reaction rates with temperature, in order to establish a flame in the attachment region, the mixture must be ignited. This is so, because the spontaneous ignition length of the fuel air mixture is of the order of U_1 times the adiabatic explosion time, evaluated for the stoichiometric mixture of the fuel with air at their initial temperatures T_∞ , and this is too long for the reaction to occur in the combustion chamber. Therefore, ignition must be accomplished artificially by local heating of the mixture; then propagation along the mixing layer must take place until the flame is anchored at the attachment region of the splitter plate, if the jet velocity is smaller than a critical value of flame detachment; for higher values the flame will be lifted to a lift-off distance, see Peters (1984).

2. CURVED FLAME FRONT PROPAGATION

In order to describe the process of flame propagation along mixing layers, Dold (1987) has presented an asymptotic analysis based on the large typical values of the activation energy of the reaction. Even though the effects of the thermal expansion are not accounted for in Dold's original analysis, it can be generalized to include these important effects.

When the flame is established in a mixing layer, where the mixture fraction Z varies from 0, on the air side, to 1, on the fuel side, it becomes curved because it moves faster along the stoichiometric surface $Z=Z_s$ than on the air side, where it is lean, or on the fuel side, where it is rich. Notice that a diffusion flame, lying along the stoichiometric surface $Z=Z_s$ is left behind the curved flame front. In this flame the temperature is the adiabatic flame temperature T_f for the stoichiometric mixture fuel and air, if the Lewis numbers are equal to one.

The premixed flame temperature T_b drops rapidly from T_f , when moving away from the stoichiometric surface. If the Zeldovich number $\beta = E/RT_f$ is large, the local flame velocity decreases by a factor of order unity when the variation of Z from Z_s is of order $1/\beta$, and the flame bends backwards rapidly in a distance δ_m/β . This is the characteristic size of the nose region of the curved flame front, small compared with the characteristic width δ_m of the mixing layer.

If we use a reference system moving with the curved flame front the process appears steady and quasi two-dimensional. Even when using the thermal diffusive model, the analysis becomes very complicated if one looks, as Dold does at the distinguished limit for which δ_m/β is of the order of the characteristic preheat zone δ_p , of the stoichiometric flame (of velocity U_p such that $U_p \delta_p / \nu_\infty = 1$). If we consider the flame front propagation process for values of $\delta_m/\beta \delta_p \gg 1$ viscous and diffusion effects can be neglected outside the thin curved flame, and flow deflection, due to the thermal expansion in the flames, can be accounted for in the analysis. The density can be considered constant, equal to ρ_u , upstream of the flame, and also downstream, where the changes in ρ from the adiabatic flame value ρ_f are of order ρ_f/β .

Similarly, we can also neglect the changes in the flow velocity, relation to the front, of the incoming stream from its value U associated with the stoichiometric surface, because they are $1/\beta$ times the velocity difference across the mixing layer. Hence the flow upstream of the flame front is irrotational with a stream function ψ that satisfies the equation

$$\Delta\psi = 0. \quad (1)$$

The mass fraction of fuel and oxidizer as well as the mixture fraction are conserved along the streamlines, and are therefore known linear functions of ψ determined by the incoming upstream state. The temperature and the stagnation pressure are also constant ahead of the flame front.

Downstream of the flame front there is vorticity ω generated at the flame, which is conserved together with the stagnation pressure along the streamlines, so that the stream function ψ satisfies the equation

$$\Delta\psi = -\omega(\psi). \quad (2)$$

The function $\omega(\psi)$ is obtained from the jump conditions across the flame, in terms of the local normal flame propagation velocity u_n , a known function of the local upstream composition and therefore of ψ .

The resulting non-linear problem includes the flame front position and front velocity U as unknowns to be obtained as part of the solution.

As a consequence of the gas expansion associated with the moderately large value of ρ_u/ρ_f the streamlines diverge before approaching the flame, and the velocity along the stoichiometric surface is reduced from U to u_p at the flame.

The ratio $U/u_p > 1$ is only a function of Z_s and the density ratio ρ_u/ρ_f . If the flame front velocity U is larger than the local velocity at the stoichiometric line the front will move upstream, otherwise it will be

locally blown down. In the first case there is the possibility that it will move upstream until it reaches the splitter plate or lip of the injector.

3. STRUCTURE OF THE FLAME ATTACHMENT REGION

As indicated before, the size of this region, δ_N is such that the local Reynolds number is of order unity, and the complete quasi-steady form of the Navier-Stokes equations, augmented by the conservation equations of energy and species, must be used for the description of the flow in the region, and therefore of the flame attachment process. However, for the typically large values of the Reynolds number $U_1 a/\nu_\infty$, this region is embedded in a much larger region where the flow can be described using the boundary layer approximation, and the Burke-Schumann limit of infinite reaction rates can be used to describe the diffusion controlled combustion. See Williams (1985).

The structure of the outer region is slightly different in the cases where there is a non-zero flow velocity U_0 on the air side, and the case where the air is originally stagnant, see Daniels (1977). In the first case the boundary layer approximation fails in a tripple deck region, close to the splitter plate end but external to the Navier-Stokes region, where the pressure decreases below the ambient. In the second case this lowering of the pressure in the near wake region is not so strong, and matching of the Navier-Stokes (N-S) region with the outer boundary layer region is possible. It must be pointed out that in this region, the viscous and diffusion effects are confined, just downstream of the plate, to a thin mixing sublayer placed along the deviding streamline that without diffusion would separate the fuel and air. The velocity along this line and the thickness of the mixing layer grow, in this Goldstein region, as the cubic root of the downstream distance.

The size δ_N of the Navier-Stokes region is related to the size δ_B of the fuel boundary layer when it reaches the splitter plate end. This is equal roughly to a if the flow is of the Poinseuille type upstream, otherwise $\delta_B \ll a$. When leaving the (N-S) region toward the fuel side the velocity should grow at the same linear rate shown by the fuel boundary layer close to the wall. On the air side of the (N-S) region the longitudinal velocity component should tend to zero, if the air is stagnant. These matching conditions allow us to obtain the scales for the velocity U_N and length δ_N of the Navier Stokes region. Namely,

$$U_N/U_1 = \delta_N/\delta_B \quad (3)$$

which together with the relation

$$U_N \delta_N / \nu_\infty = 1 \quad (4)$$

determines both U_N and δ_N .

When comparing the residence time, δ_N/U_N , in this region with the characteristic reaction time at the adiabatic flame temperature T_f , or, equivalently, with the residence time accross the stoichiometric planar flame δ_p/U_p , we obtain a Damköhler number D . This, together with the Zeldovich number $\beta = E/RT_f$ and the temperature ratio T_f/T_∞ , are the main parameters left, when the conservation equations and boundary conditions are written using U_N and δ_N as scales.

One can anticipate that the solution of the resulting problem is multivalued for $\beta \gg 1$, showing the existence of two solutions with attached flames for values of D larger than a critical value D_c . If the plate is not thermally insulated the flame will be quenched upstream of a flame standoff distance from the plate δ_q of the order of δ_N , which is a function of D

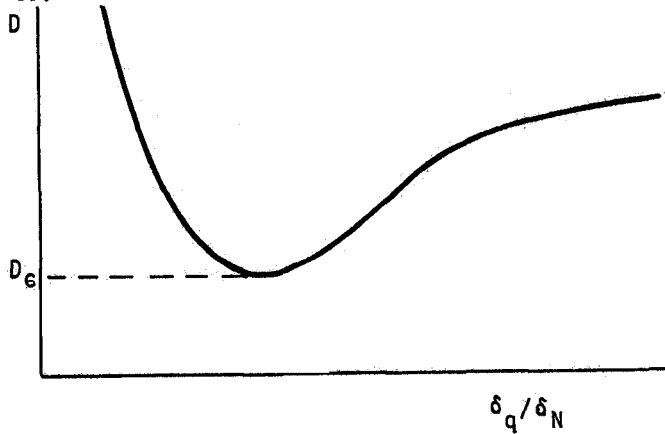
of the form shown in the figure.

The branch corresponding to the larger values of δ_q may correspond to a flame front anchored at the Goldstein region, but it is unstable.

The details of the analysis sketched here will be presented in a paper under preparation to be published elsewhere.

ACKNOWLEDGMENT

This research has been partially sponsored by the Spanish CAICYT under Project no. 2291-83.



REFERENCES

1. Dumont, J.P. and Borghi, R., A Qualitative Study by Laser Tomography of the Structure of Turbulent Flames. Combust. Sci. and Techn., Vol. 48, p. 107 (1986).
2. Peters, N., Laminar Diffusion Flamelet Models in Non-premixed Turbulent Combustion. Prog. Energy Combust. Sci., Vol. 10, p. 319 (1984).
3. Dold, J.W., Flame Propagation in a Non-uniform Mixture: Analysis of a Slowly-Varying Tripple Flame. Bristol Univ. Report No. AM-87-02 (1987).
4. Williams, F.A., Combustion Theory, Benjamin Cummings (1985).
5. Daniels, P.G., Viscous Mixing at a Trailing Edge, Quart. Jl. Mech. Appl. Math., Vol. 30, p. 319 (1977).